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Transpiration from Maize

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The aim of this note is to estimate the amount of transpiration from a tall crop (such as maize), relative to the amount from a shorter crop (grass), assuming the latter to be known. Penman's formula is used and figures are presented to show the variation of tall to short crop relative transpiration with roughness height of the crop and leaf resistance. The results would be applicable to transpiration averaged over a period of several weeks, and to crops which form a uniform dense canopy, rather than crops grown in rows, with clear spaces between, where "standing eddies" may form.

Transpiration

Penman's formula is

$$LE = \frac{\frac{\Delta}{\gamma} H + \frac{\rho C_p d_a}{\gamma r_a}}{\frac{\Delta}{\gamma} + \left(1 + \frac{r_s}{r_a}\right)} \qquad (1)$$

where,

L is the latent heat of vapourisation

E is the mass flux of water vapour

Δ is the gradient of the vapour pressure-temperature curve

H is net radiation

ρ is air density

C_p is specific heat of air at constant pressure

d_a is vapour pressure deficit at height Z above the ground

r_a is resistance to vapour flow from the crop surface to height Z

γ is psychrometric constant

r_s is resistance to vapour flow within the leaf

r_a is given by,

$$r_a = \int_{z_o}^{Z} \frac{dZ}{K_W}$$

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z_o is the roughness length of the crop. K_w is the transfer coefficient for water vapour, which in neutral conditions is assumed equal to coefficient for momentum transfer, $K_M = kU_* z$. k = Karman's constant, U_* = friction velocity.

We get,

$$r_a = \frac{1}{kU_*} \ln \frac{z}{z_o} \qquad (2)$$

assuming the logarithmic wind profile,

$$r_a = \frac{\left[\ln z/z_o\right]^2}{k^2 U(z)} \qquad (3)$$

U(z) is the wind at height z.

Equation (3) has been used in (1) by several authors (eg Van Bavel, 1966) and gives better estimates of E than if constant r_a were used. It has the disadvantage however, that the vapour pressure deficit and wind speed at height z have to be known for different crop surfaces before any comparison can be made between their respective transpirations.

The proposal is to use equation (2) in (1), and to make z sufficiently large to ensure that d_a is nearly the same over the different crop surfaces. Graphs have been published (Monin and Zilitinkevich, 1967, and at the end of this note) which show the variation of U_*/V_g with surface Rossby number $R_o = V_g/f z_o$. (V_g is the geostrophic wind and f the Coriolis parameter). A value for z of 100 m was thought sufficient to ensure that d_a would be approximately the same for crops of different roughness. This choice for z and the use of equation (2) assume a constant shearing stress in the layer from the ground to 100 m at least.

Variation of Transpiration with Surface Roughness

To show the variation of E with z_o it is assumed that net radiation, H, does not change as the crop becomes taller and that the air temperature (and hence Δ) are also equal. The factors affecting evaporation are then r_a, r_s and the relative contributions of the net radiation term $\Delta H/\gamma$, and the aerodynamic term $\rho C_p d_a/\gamma\, r_a$. The ratio of these last two terms for a short crop such as grass, is called f, ie:

$$f = \frac{\Delta H/\gamma}{\rho C_p d_a/\gamma\, r_{ag}}$$

r_{ag} is the diffusion resistance for the short crop. During mid summer in SE England f lies between 2 and 3 when averaged over periods of several weeks. Let n be the ratio of the values of r_a for the rougher surface (r_{aR}) to the less rough surface (r_{ag}), then

$$n = \frac{r_{aR}}{r_{ag}} = \frac{\ln 100/z_{oR}}{\ln 100/z_{og}} \cdot \frac{U_{*g}}{U_{*R}} .$$

Suffix R refers to the taller (rougher) crop and g to the shorter crop (grass). z_o is in metres. The ratio of the transpirations for the tall and short crops E_R/E_g can be expressed in terms of f, n, r_s and r_{ag}.

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$$\text{ie } \frac{E_R}{E_g} = \frac{(f + \frac{1}{n})\ (\frac{\Delta}{\gamma} + 1 + r_s/r_{ag})}{(f + 1)\ (\frac{\Delta}{\gamma} + 1 + r_s/n\, r_{ag})} \qquad (4)$$

Once reasonable values for f and r_s/r_{ag} have been chosen it is then possible to obtain the variation of E_R/E_g with surface roughness.

When r_s = o, the leaf imposes no resistance and the ratio of potential transpirations is obtained as

$$\frac{E_R}{E_g} = \frac{(f + \frac{1}{n})}{f + 1}$$

When the leaves are not actually coated with water most crops impose a slight resistance to vapour flow and typical values of r_s/r_{ag} are between 0.1 and 0.3 (Monteith, 1965).

Calculation of E_R/E_g

1. Short crop assumed to have a z_o = 0.2 cm

2. Values of U_*/V_g read from the neutral curve (4b)

3. V_g assumed to be 5 m/sec which is a reasonable value for midsummer in SE England

4. Δ/γ taken to be 1.86, corresponding to a temperature of 62°F; f was taken as 2 or 3.

Figure 1 shows E_R/E_g plotted against z_o. The solid lines are f = 2 and show the effect of leaf resistance with r_s/r_{ag} taking the values 0, 0.1, 0.2, 0.33, 0.5 and 1.0. The graph shows that transpiration increases with z_o, but that increasing the leaf resistance r_s, is very effective in lessening increases in transpiration. Curves for f = 3 are also shown (pecked line) when r_s/r_{ag} takes on the values 0, 0.2 and 1.0. This shows that an increase in f (more sunshine or more humid atmosphere) reduces E_R/E_g, and that when r_s is sufficiently large a tall crop actually transpires less water than the short crop with the same r_s. When f is increased to 4, E_R/E_g is reduced to 0.93 for a tall crop (z_o = 20 cm) with r_s/r_{ag} equal to 1.0.

The turning point value of f can be found by differentiating E_R/E_g with respect to $\frac{1}{n}$ and equating to zero. The condition is that

$$f = \frac{\Delta/\gamma + 1}{r_s/r_{ag}}\ .$$

Using r_s/r_{ag} = 1.0 and Δ/γ = 1.86, then f = 2.86. When r_s/r_{ag} takes on the more usual (in this country) value of 0.2, the turning point is f = 14.3, an unlikely value in this country.

Criticisms of the Method

1. Assumes horizontal homogeneity of the underlying surface

2. It relies on reading U_*/V_g values from a graph. The ratio of U_*'s for tall crops to the short crop is shown in figure 1. There is some sort of discontinuity between z_o = 4 and 6 cm which is reflected in all the other curves also. This may be due to the way in which Monin and Zilitinkevich drew their curves.

3. Calculations have been done for V_g = 5 m/sec. Different values can easily be used, but with the added complication of the variation of z_o with windspeed. The general effect of this would be to reduce the E_R/E_g ratio as V_g increased.

4. r_a values refer to neutral conditions. When evaporation is large most of the net radiation is used to supply the energy for this and it is reasonable to assume near neutral conditions. As r_s increases the turbulent heat flux increases at the expense of evaporation, with more unstable conditions. Due to this the curves for r_s/r_{ag} = 1.0 or 0.5 say could be wrong.

5. The assumption is made that r_s for the short crop (grass) is equal to r_s for the tall crop no matter what it is. It is reasonable for most farm crops, but would not be true for citrus which have larger r_s values than grass even when well watered (Van Bavel et al, 1967).

6. Assumes equality of da above all crops at z = 100 m.

7. Assumes equality of moisture and momentum transfer in the derivation of r_a.

Some support for the curves in fig 1 comes from measurements made in Australia (Evans, 1971). A graph is presented which shows the ratio of daily transpiration from rice to evaporation from a pan of water. r_s is zero for the pan water and probably nearly zero for the rice. z_o for the rice varied between 1 and 19 cm and z_o for the pan plus surroundings was apparently about 3 cm. The trend of the points in Evan's graph is similar to the figure 1 curves and the values of rice to pan evaporations are in reasonable agreement with the figure 1 values with f between 2 and 3 and r_s/r_{ag} = 0.

Application to Maize

During June after a complete canopy has grown the plants may be about 100 cm high, with $z_o \simeq$ 10 cm. In this country leaf resistance is fairly small and the maize would use about 30% more water than a short grass crop under the same weather. During the grain filling stage little change in height occurs so that from the end of July to harvest the maize uses about 40% more water than grass. If the weather is very dry during this period, r_s will increase and E_R/E_g may be reduced to 1.2 or less. The increase in f also associated with dry weather would also decrease the differences between tall and short crop transpiration.

Any comments should be sent direct to the author.

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Monin, A S and Zilitinkevich, S S	1967	Report of the study conference on The Global Atmospheric Research Programme. Appendix V, Stockholm 28 June - 11 July 1967. ICSU/IUGG - Committee on Atmospheric Sciences
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Van Bavel, C H M	1966	Potential Evaporation: The Combination Concept and its Experimental Verification. Amer. Geophys. Union Water Resources Research, Vol 2, No 3, p 455-467
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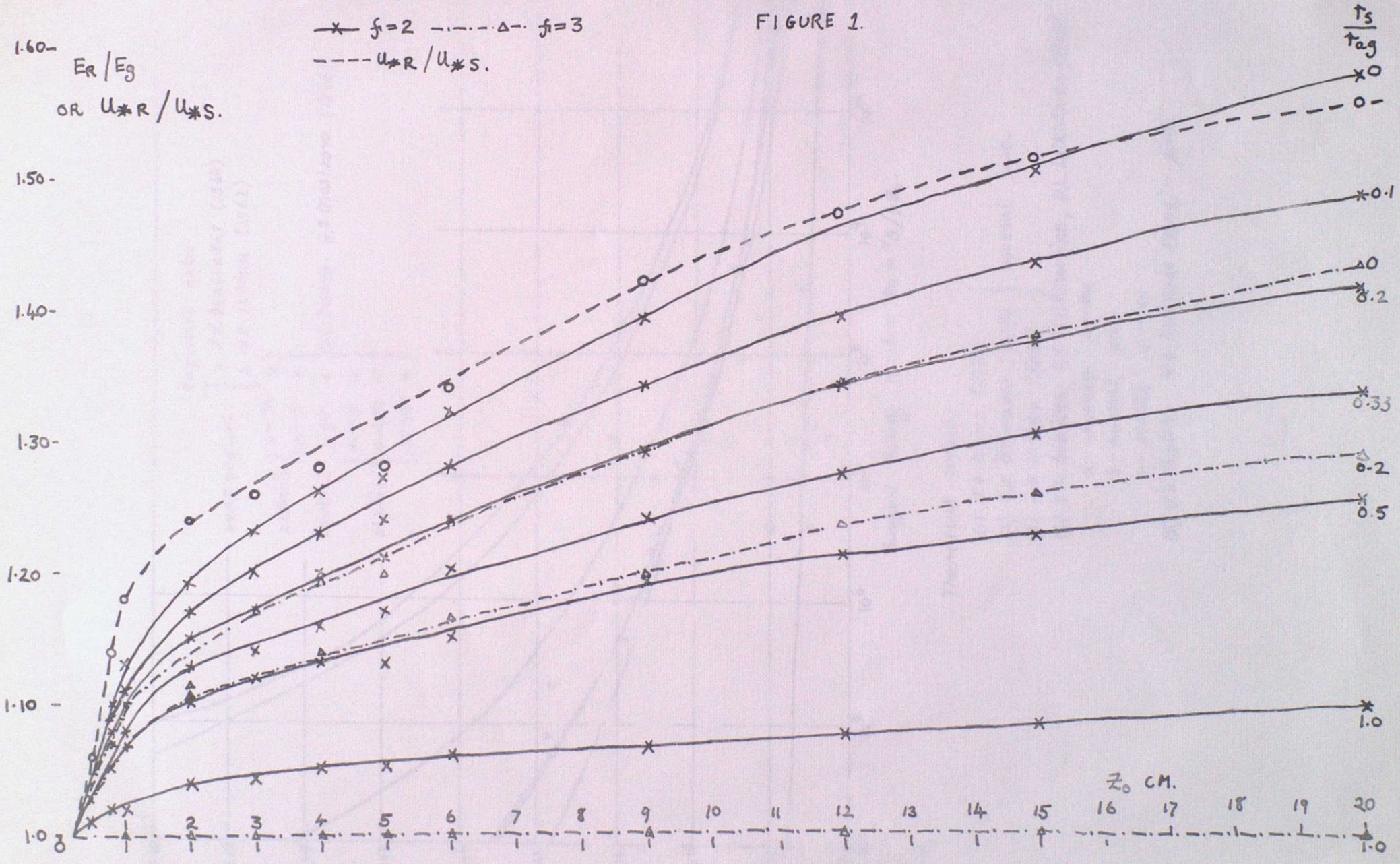
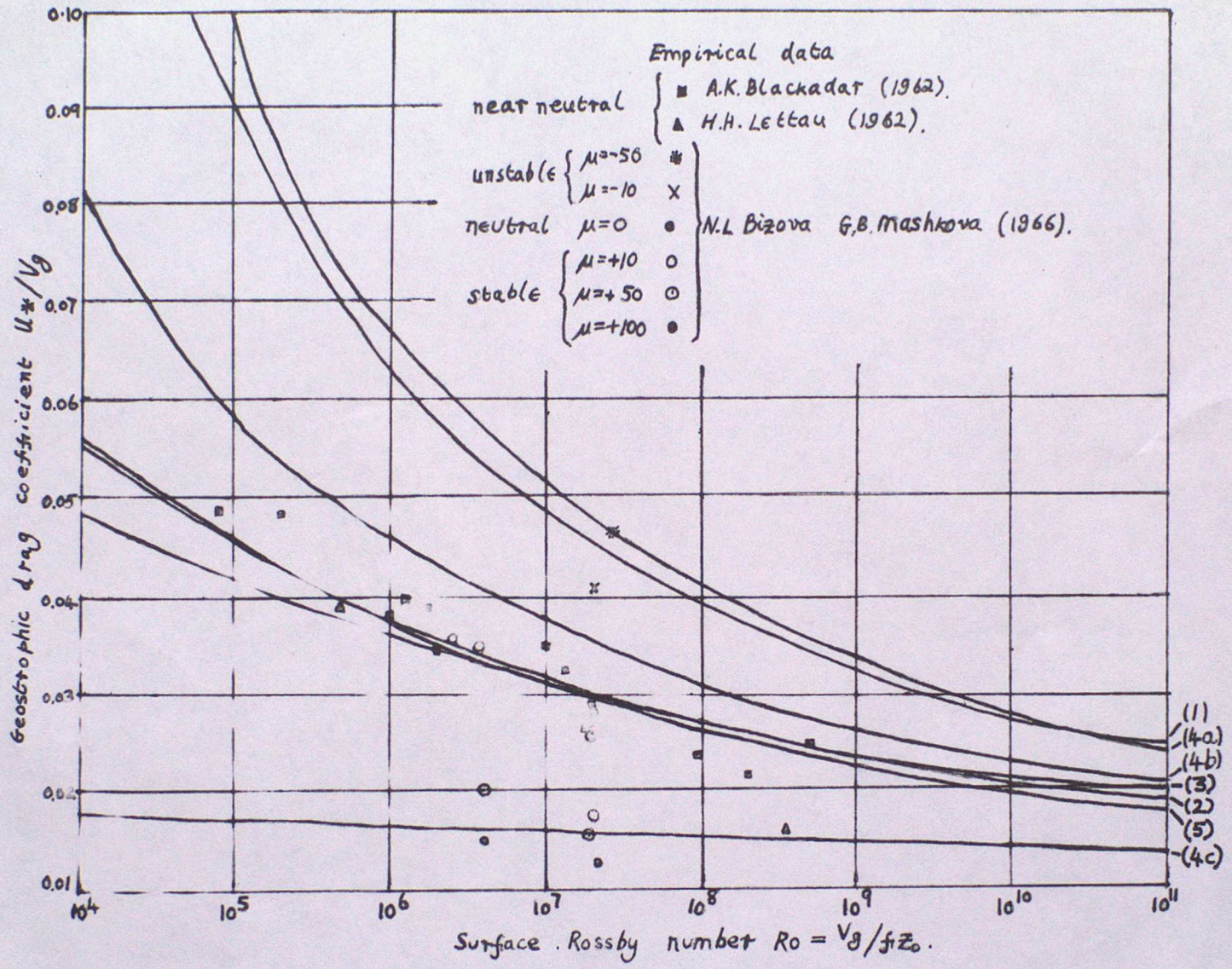


FIGURE 1.
—x— fr=2 -.-.-.-Δ-.- fr=3
---- u*R / u*S.
ER / Eg
OR u*R / u*S.
1.60
1.50
1.40
1.30
1.20
1.10
1.0
τs / τag
0
0
0.1
0
0.2
0.33
0.2
0.5
1.0
Z0 CM.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
1.0



Theoretical curves:

(1) A.S. Monin (1950).
(2) A.K. Blackadar (1962)
(3) H.H. Lettau (1962)
} neutral $\mu=0$.

(4) I.M. Bobileva, S.S. Zilitinkevich, D.L. Laikhtman (1965).
a - unstable $\mu=-100$
b - neutral $\mu=0$
c - stable $\mu=+100$

(5) J.F. Appleby, W.D. Ohmstede (1966) - $\mu=0$.